GMM Property Committee

December 12, 2009

Goal: improve sustainability of Meeting by reducing its use of fossil fuels.

1. History

Our historic meetinghouse was designed to maintain a comfortable indoor environment in both winter and summer. The high ceiling allows hot air to rise, and the 24" stone walls provide natural cooling. The meetinghouse was originally designed to be heated by a coal furnace, which over the years has been upgraded to heat with oil and natural gas. The furnace generates low-pressure steam which allows radiators hidden beneath the windowsills to warm the rooms. Originally (1870) the radiators were supplied with air by convection through vents in the central floor. Later, (1930s) a system of air ducts, heat exchanger, and a blower was installed to increase the heating capability. More recently (1970), the blower has been turned off and the heating ducts again run by convection. The dual-supply steam boiler can run from oil or natural gas, however much of the heat it generates is lost to the chimney flue.

Figure 1. Germantown Meetinghouse in 1870. When constructed it was considered a modern and efficient building, but its heating system and lack of insulation are inefficient and contribute to global warming.

Insulation

The design of the Meetinghouse was considered to be state of the art 150 years ago and has several notable features. The circular vent in the meeting room ceiling allows summer heat to rise into the attic where it is vented to the outside. The walls have considerable thermal mass which accumulates heat and radiates it over a 12-hour period. These features are a benefit during both summer and winter. During the summer, the Meetinghouse walls are cooled by the night and early morning temperatures and stay cool throughout the morning and well into the afternoon. The window blinds can be adjusted to prevent heat accumulation from the windows facing the sun. During the winter, the ceiling vent can be closed to prevent drafts, the window blinds can be closed to reduce heat loss, and the walls once heated will continue to supply heat for the entire day. The entry vestibules reduce heat lost when the doors are opened. In the middle 1900s, insulation was installed between the rafters to reduce the heat lost through the ceiling during winter.

However, when compared to modern standards, the thermal insulation in the Meetinghouse is woefully inadequate. To discuss the amount of insulation, we must understand how it is specified and measure. The R-value of insulation specifies how many degrees difference across the insulation when a standard amount of heat is flowing through it.

One R-value is

R-value = ft^2 * degF * h / BTU

Where:
1 BTU = 1 lb water 1 degF

Conversion factors:
1 R-value = 0.176 degC*m2/W
1 degC*m2/W = 5.674 R-value
1 watt = 3.41 BTUs/hr

The insulation in our ceiling is approximately R-12. This was the standard several decades ago but the modern standard is R50. Part of the problem is that the uncovered insulation has an open surface which allows cold air drafts to infiltrate through the volume of the rock wool. A draft protection of some sort, for example insulation batts covered with paper, or closed-cell foam, would prevent the problem. The rock wool insulation could be replaced with foam insulation to give us much greater R-value in the same space. Foams differ in their flammability and we should install the most efficient and least flammable type.

The windows and walls of the Meetinghouse are virtually uninsulated. The R-value of the Meetinghouse's stone walls is weak because stone has little insulating value. The walls are 24" thick, and the R-value of this type of construction is ~0.15/inch, for a total of R-3.6. Adding together the components of the wall gives R-6.5. The windows are worse at R-2, but they comprise only 10% of the wall area:

R-value of walls:

Outside air film = R-0.17
Stucco = 0.15/inch * 0.5" = R-0.07
Stone wall, 0.15/inch * 24" = R-3.6
Air space, 1" = R-1
Wood lath, plaster = R-1
Inside air film = R-0.68

Total = R-6.5

R-value of windows:

Storm window = R-1
Window sashes = R-1

Venetian blinds = R-0.68

Total = R-2.7

The area of the windows is approximately 10% of the total exterior area of the meetinghouse:

Total exterior area	= 891.8 m2
Total window area	= 93.6 m2
Total exterior area minus windows	= 798.2 m2
Total ceiling area	= 844 m2

Heating system. Our heating system is a double-source furnace which can be run on heating oil or natural gas. This allows us to take advantage of lower prices of either fuel when there is a price differential. However, the furnace is rather inefficient and expensive, costing us $8000/year, even though the main rooms of the building are only occupied for ~15 hours/week during the winter months. We would like to reduce our use of energy to save money and to reduce our use of fossil fuels. If we could increase the insulation value of the walls and windows, the building would not require as much energy which would reduce our cost and also our use of fossil fuel.

Recommendations for reducing our energy use.

1) NPS standards for historic buildings. The National Park Service has commissioned a series of briefs to aid in preserving, restoring, and maintaining historic buildings (see references below). A brief on conserving energy in historic buildings makes several important points. The building should not be modified to change its historic character. For example, the original windows should be preserved if possible in preference to being replaced. Storm windows and doors can reduce heat loss but they should be carefully considered so as to minimize the visual impact on the building's appearance.

2) Upgrade the insulation in the Meetinghouse ceilings. Currently the attic insulation of the Meeting and Committee rooms is R-12. If we upgrade this insulation, we can reduce heat loss through ceilings by 50%-75%. We can remove the old rock-wool insulation and add new foam insulation, making sure to install a vapor barrier surface on the bottom. The rafters are deep enough (10") that we could install enough foam to provide R-50 insulation. The job would require careful attention to fitting the foam panels and sealing around the vapor barrier to prevent moisture condensation. The best modern foam insulation is polyisocyanurate which has an R-value of R-6 per inch, and good resistance to flammability.

3) Upgrade the storm windows to reduce drafts and heat loss. A double or triple-glazed storm window can achieve a 5-fold reduction in heat loss. The most efficient storm windows comprise several components to reduce heat loss: the space between the panes is filled with low-heat-conducting gas, and the glass itself has low-emission coatings. Our Meetinghouse has several single-pane windows around the doors in the vestibules, kitchen and office which need immediate attention.

Double-insulated glass windows can dramatically reduce heat loss but are expensive and have a limited lifetime (~15-25 years). They typically can fail when the seals between the 2 panes of glass break due to thermal stress (see references below). This may allow water vapor to enter between the 2 panes, causing fogging of the window. However, even with such a limited lifetime, the insulated window will more than pay for itself in terms of savings. Further, the thermal stress can be avoided by a covering the dual insulated glass with a single-pane window, increasing the life span of the dual-insulated window to ~50 years. This system would effectively mean a triple-insulated system and would be too heavy for opening, but it could be applied very effectively to the meetinghouse's upper windows which do not require opening.

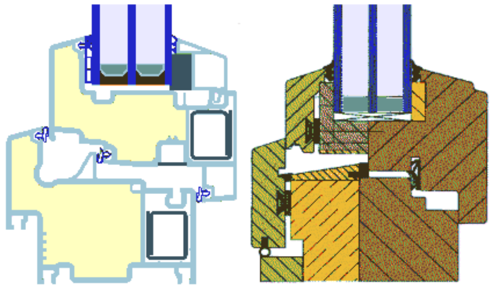

Figure 2. Triple-insulated windows used in passive solar-heated houses in Germany. Left, vinyl covered sashes, right, wood sashes. Each pane increases the R-value by 1, and argon filling and low-emissivity coatings also increase the insulation value, for a total approaching 10 -- a reduction of the heat loss by 10-fold from a single pane window.
From www.wikipedia.org.

R-factors for typical glazing assemblies

	Thermal conductivity U-factor		Thermal resistance R-value	
units ->	W/m2/K	BTU/(h*ft2*°F)	m2K/W	h*ft2*°F/BTU
single glass	6.25	1.10	0.16	0.90
standard dual-pane IGU (in US)	2.84	0.5	0.35	2.0
Medium-Solar gain, low-e	1.48	0.26	0.68	3.8
European triple glazed	1.00	0.18	1.00	5.7
German passive house std window	0.60	0.11	1.67	9.5
Standard wood wall R-19 fiberglas	0.49	0.09	2.06	11.7

From http://en.wikipedia.org/wiki/Insulated_glazing

The right-most column shows the R-value. A single pane of glass has an R-value of ~1 which loses a tremendous amount of heat on cold winter days. A standard dual-pane glass window (either insulated or single pane with storm window) has an R-value of 2, for each pane adds R-1 to the total. Low-emissivity glass increases the R-value to 3.8, and a modern highly insulating triple pane window increases the R-value to ~10. Such highly-insulating windows are widely used for passive solar houses in Europe. They are more expensive but allow well-insulated buildings to be heated entirely by the sun, therefore justifying the greater expense.

4) Insulate the walls of the Meetinghouse. There are several possible alternatives, each a balance of cost, reduced energy use, and change in the appearance of the Meetinghouse.

a) Interior insulation. Add insulation to the inside of the Meetinghouse walls. This would require a lot of work on the interior of the walls, including stripping away the plaster/lath and reconstructing it with a good moisture barrier. The reason is that interior insulation would allow the inside surface of the stone to remain cold in the winter, which would cause any moisture escaping from the building's interior to condense on the stone. This would likely damage the wall by softening the mortar, which has occurred in other meetinghouse renovations. The NPS warns against this type of project unless the interior of the wall has little historical value, and in any case the moisture barrier must be carefully maintained. Further, insulation added on the inside of the stone wall would insulate the thermal mass of the stone from the interior of the building, preventing the benefit of its natural temperature moderation properties.

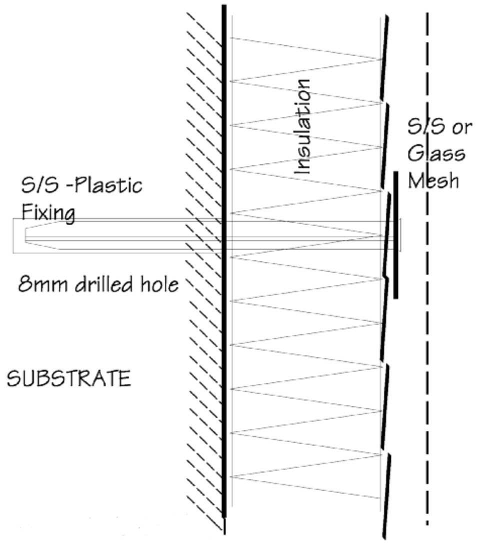

Figure 3. Method of attaching exterior insulation on temperature onto outside of building (substrate). Cross-section of wall and insulation showing the substrate, the sheet of insulation, and a stainless steel fastener that holds the insulation tight against the exterior face of the building. A mesh of stainless steel or glass fiber lath is attached to the surface of the insulation and can then be covered with a variety of stucco materials. Insulation is stiff but will shift slightly with temperature so it requires careful reinforced joints at corners and around windows. From Pearson (2006).

b) Exterior insulation. Add insulation on the outside of the Meetinghouse walls. This is the most viable method and is widely performed on stone buildings (see EIFS refs below). It preserves the thermal mass of the wall in contact with the building's interior, which helps to moderate the interior temperature. It keeps the stone warm and dry during the winter months, obviating the need for a moisture barrier on the interior surface of the wall. A system called Exterior Insulation Finishing System (EIFS) has been developed for this purpose. Panels of foam insulation are attached on the outside of a stone building with metal fasteners, and a layer of stucco is applied on the insulation. Because this system could duplicate the existing exterior stucco surface, it could potentially be applied without changing the Meetinghouse's visual appearance. Many of us have noted that the Meetinghouse's exterior appearance has deteriorated in recent years because of problems with the uneven tone of the stucco work. This would be a good opportunity to fix the appearance of the stucco.   However, as with any exterior work on our historic building, it may be necessary to apply for a Historic Landmark Alteration Certificate.

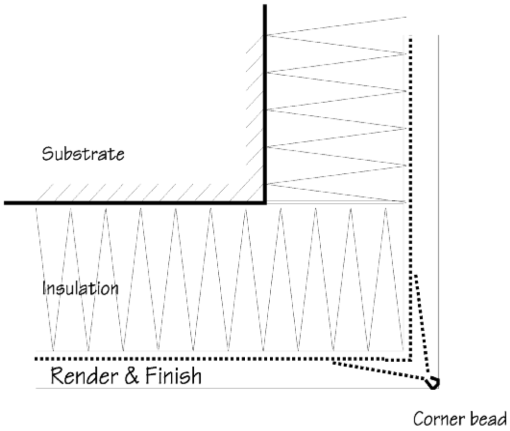

Figure 4. Detail of exterior insulation applied over corner of building (substrate). The insulation is carefully butted at corner and the joint is reinforced with stainless steel lath. A metal corner bead is attached and the surface is stuccoed. The method is designed to resist shifting from thermal stress. From Pearson (2006).

Trapped water. To prevent water from getting trapped beneath exterior insulation, flashing is installed where necessary around doors, windows, and joints to allow trapped moisture to escape. With this system, called EIFS with drainage, EIFS performs better than brick or stucco for reducing moisture buildup within a wall. Another potential concern with this system is its durability. The exterior surface of an exterior-insulated building has a lot of thermal stress because it has low thermal mass and therefore gets heated and cooled often. Therefore it is necessary to have the EIFS system applied very carefully with adequate drainage for trapped water.

Care in application. The insulation must be applied to the entire surface of the building including under the attic flooring. We would need to carefully plan how to apply the insulation under the eaves and near the attachment of the porch roof. We might remove the planking of the porch roof near the stone wall to allow the insulation to be continuously applied. Or, alternately we could apply an extra thickness of insulation surrounding the attachment of the porch roof to prevent heat from leaking out through the attachment. In addition, we would need to carefully plan how the insulation is applied around the windows. In order to preserve the exterior window appearance, we would not want to apply the full thickness of insulation flush with the windows. Instead we could apply a tapered layer of insulation with joints carefully sealed so that stucco could be applied and would be durable.

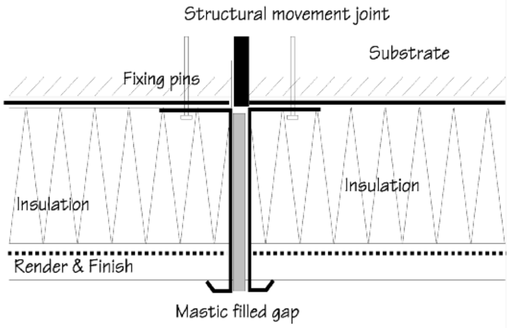

Figure 5. Detail of structural movement joint, showing two insulation panels meeting at the joint. Metal end-pieces are attached to the substrate to allow the building and insulation to shift together on either side of the joint. The exterior joint is caulked to prevent water entry. The method is designed to allow shifting from structural and thermal stress. From Pearson (2006).

5) Thermal mass. One might imagine that ideally we would want to heat up the Meetinghouse quickly for use over 3-4 hours on a typical winter morning, then lower the thermostat and allow the temperature to drop when the building is not in use. However, because the stone in the Meetinghouse wall has a large thermal mass, it absorbs a considerable amount of heat during the normal daily heating cycle. This thermal mass must be heated up, but with the stone walls as originally constructed, it does not retain the heat because the stone wall conducts heat to the outside.

Heating. If interior insulation were added to the Meetinghouse walls, we could heat the interior of the building without raising the temperature of the stone wall. However, this solution to the problem is not optimal because it would require stripping the plaster and lath inside the wall, adding insulation and a vapor barrier, and a new plaster surface. The alternative, exterior insulation, would maintain a higher average temperature in the stone wall because it would not lose much heat to the outside. During the heating cycle, the thermal mass of the stone wall would absorb the building's heat, but the exterior insulation would prevent the heat from escaping. With enough insulation, this method would retain the heat over several days or more, reducing the heat required for the next day's heating cycle. During the warmer months, exterior insulation would keep the Meetinghouse at the average day/night temperature due to the thermal mass of the stone walls.

Thermal time constant. A heated thermal mass surrounded by air loses temperature exponentially because the amount of heat it loses is proportional to the difference in temperature: as its temperature drops, the amount of heat lost also drops. The exponential fall of temperature is characterized by the "thermal time constant", which is defined by the heat capacity and the amount of thermal resistance (R-value). Calculation of thermal time constant for meetinghouse walls:

for a 1 m2 section of 24" (60 cm) wall and R-5.7 insulation (R-5.7 = K*m2/W),

$$60 \text{ cm} * \frac{1e4 \text{ cm2}}{\text{m2}} * \frac{2.3 \text{ g stone}}{\text{cm3}} * \frac{0.8 \text{ J}}{\text{g stone} * \text{K}} * \frac{\text{W} * \text{s}}{\text{J}} * \frac{\text{K} * \text{m2}}{\text{W}}$$

Where:
Wall = 60 cm of stone
Density of stone = 2.3 g/cm3
Heat capacity of stone = 0.8 J/g/K
Insulation = R-5.7 = 1 * K*m2/W
Energy equiv = Joule = W*s

6*2.3 * 0.8 * 1e5 s = 1.1e6 s =~ 306 hours = 13 days

So, for 4" of polyisocyanurate foam, at R-5/inch, we could insulate the meetinghouse walls to to R-20, and the 24" walls would have a time constant of

13 days * 20/5.674 = 45 days

This assumes that the air inside the meetinghouse is the same temperature as the walls, which is reasonable if the insulation is placed on the wall's outside surface. Thus, the meetinghouse walls when insulated with 4" of foam could store their heat for several weeks. Once heated, the meetinghouse would tend to hold its heat, which would reduce the need to be fully reheated every day.

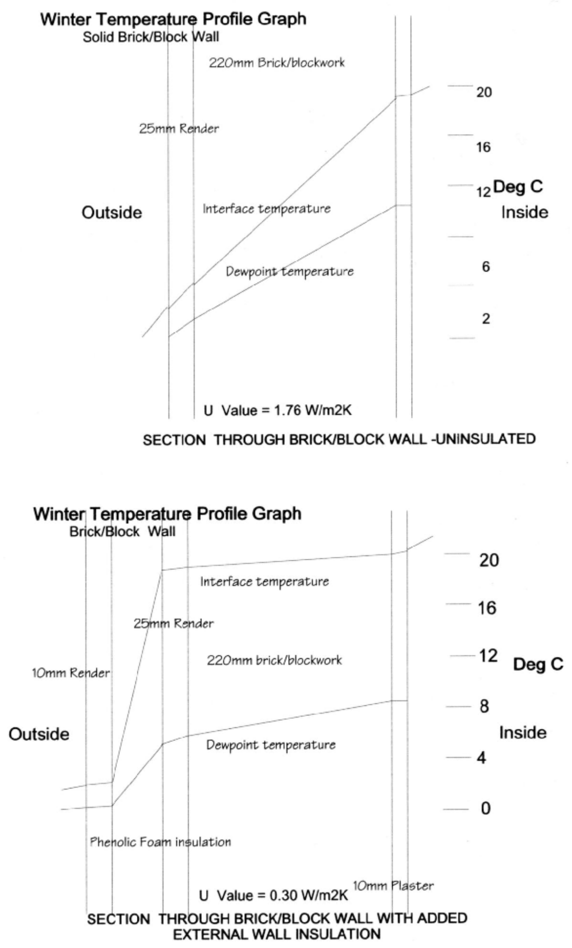

Figure 6. Effect of external insulation on temperature gradient in a stone wall. Cross-section of wall showing profiles of temperature and dewpoint for uninsulated wall (top) and insulated wall (bottom). The external insulation incorporates most of the thermal gradient, leaving the stonework at the interior temperature. The dewpoint (the point at which humidity condenses on a cold wall) remains beyond the wall's exterior. From Pearson (2006).

Cooling. A further advantage of the thermal mass and an increase in time constant provided by exterior insulation would be cooling during the summer months. Because the average temperatures during May and June are low, the meetinghouse walls would remain cool and would therefore tend to cool the building during the daytime hours. Later in the summer, when average temperatures rise, the walls' thermal mass would moderate the daytime heat, and during the fall months the building would remain relatively warm as nighttime temperatures fall.

6) Convert from steam to super-efficient hot-water system. Our present furnace and heating system is ~50% efficient, with much loss of heat in the piping and up the chimney. A modern super-efficient system could reduce this loss by half. However, the most efficient heating systems use hot water. Our system could be converted to hot water, but the existing radiators and pipes will not work correctly for a hot water system. Most of the radiators in the Committee & Social Rooms will work only with steam. However, if we could reduce the amount of heat necessary to heat the building through installation of insulation and better storm windows, we could convert our system to a hot water system.

The existing steam furnace and radiator system can heat the Meetinghouse in about an hour, even though many of the radiators are located under the floor inside air ducts beneath the windowsills. The reason is the high temperature of steam. A corresponding hot-water system has some disadvantages but also several advantages. A hot-water system takes longer to get up to working temperature because there is a greater mass of water in the radiators to be heated. Hot water radiators also cannot transfer heat to the air as efficiently because hot water (130-150 deg F) is cooler than steam. But a hot-water system can be more efficient overall than a steam system because modern hot-water furnaces can transfer most of their heat into the water. A major benefit of a hot-water system is that it can also tie into a solar or geothermal heating system.

In a consultation with a local plumbing contractor we received the advice that the Committee and Social Rooms could be heated most efficiently with several small furnaces in parallel, with each furnace turning on to give more hot water when required. We could remove the existing radiators and replace them with hot water models, or we could install radiant heating in the floor. A radiant heat system could be a thin layer of tubing installed underneath the carpet, which would gently and evenly heat the room without the use of visible radiators. This type of system is widely used and is efficient and quiet. Either of these types of system could be tied into sustainable sources of heat such as a geothermal heat pump or a solar energy system. Another possibility would be to install an air-to-air heat pump.

Before we can consider the specific details of improvements to heating the Meeting and Committee Rooms, we need to improve the insulation on the Meetinghouse walls. The reason is that insulation can potentially reduce energy use by ~4-fold, so a more efficient heating system should be smaller than what is currently required to heat the Meetinghouse. In order to correctly specify the type and capacity of our heating system, we need to know how much heat is required. Therefore we should plan to carefully upgrade the Meetinghouse's insulation first.

7) Air conditioning. Over the summer of 2009, an air-to-air heat pump was installed in the office to provide air conditioning in the summer as well as heat during the winter. Previously the furnace under the meeting room was required to fire up to heat the Office, which then lost heat in the pipes running from the furnace through the basement to the Office. The separate heat pump for the Office provides an immediate reduction in energy use and gives better control of the Office temperature. The main advantage of the heat pump is that when only the office need be heated, the main furnace under the meeting room need not be fired up. Thus, we project that the heat pump will pay for itself in 3-5 years.

Although traditionally we have not seen the need for air conditioning during the summer, there are times in June or September when it might be helpful for the Committee Room. However air conditioning could cause problems with condensation on the walls. With air conditioning and external insulation, the stone walls would be cooler than the outside air, and therefore to prevent condensation we would need to install a very complete vapor barrier under the insulation on the outside of the stone wall. This might be accomplished by extra care in the installation and sealing around the exterior insulation. This system might be viable for the Office, which is currently hot in the summer and cold in the winter.

Several advantages of insulation. Overall, the effect of insulating the meetinghouse would be several-fold: a) reduce heat lost to the environment, b) increase the thermal time constant (duration of effect of heating) of the meetinghouse walls, c) allow the use of a hot water system, which could d) tie into a solar or geothermal heating system. All of these would provide savings and increase our sustainability.

8) Hot water system is compatible with heat pump. If we convert the furnace to a hot-water system, we could add a heat pump system which would be more sustainable. A heat pump is like a refrigerator in reverse, i.e. it takes heat from outside the building and concentrates it to a higher temperature to heat the building. A heat pump requires a reservoir from which to pump the heat, which can be the outside air, a large water reservoir, or the earth. The new GFS science building and Friends center rely on geothermal heating, where a heat pump concentrates the heat from the earth.

Such a geothermal heat system is compatible with a super-efficient condensing hot-water furnace. The furnace can deliver heat when needed to backup the other sources. Because both geothermal and hot water furnace systems work within the same temperature range, they are compatible and can be combined to make a more efficient system.

9) Geothermal heat pump. The system that heats Friends Center has six 1000' wells each with a loop of piping that circulates cool water down into the earth and returns warmer water. The heat from this circulating water is exchanged through a heat exchanger, then sent to a water-to-water heat pump which raises the temperature high enough (80-90 degF) to be directly circulated through baseboard and radiant heating units and water-to-air heat exchangers. In the summer, the system is run in reverse, circulating warm water down into the earth, returning with cooler water for the heat pump to cool further for air conditioning. The GFS Science building has a similar system. We might install this type of system for the GMM Meetinghouse to provide heat when solar energy is not available. The advantage of a geothermal heat pump system is its reliability. Whenever heat is required, it can be provided simply by turning on the well circulator pumps and the heat pump. The operating cost is the electricity required to run the heat pump, which although high is typically 3- to 10-fold more efficient than electric heat, making it competitive with heat from fossil fuels. When the electricity to run the heat pump is obtained from solar or wind power, the geothermal heat is sustainable. If we super-insulate the Meetinghouse, we could heat it very reliably and effectively with a heat pump.

10) Solar heat. We could combine a heat pump with a solar heating system. With enough solar panels, the solar system heats the building during the daytime, but provides enough extra collection capacity, along with a system of heat storage, to heat the building through the night or a period of cloudy days. In the simplest solar system, we could place solar panels on the SE and SW facing walls of the meetinghouse and the porch roof. A set of 20 - 4' x 8' panels would provide 25 kW of heat, 4-fold more than required to heat the super-insulated meetinghouse on a sunny day. Because sunlight is available to a stationary solar panel only 6 hours in a typical sunny day, the 4-fold excess would allow us to heat the meetinghouse over a 24-hour period. To provide heat during cloudy spells, a modest excess of solar collectors would allow storing some heat. With a sufficiently large heat storage, the system could heat the meetinghouse during a cloudy spell of several weeks. A small system of heat storage, sufficient for a few days, could consist of some insulated hot water tanks with pumps and insulated piping, and could be located in the basement.

Such a system of solar heat with storage could be combined with a heat pump in several ways. A heat pump could use the heat storage as its exterior reservoir to obtain more heat out of the storage. Alternately, a geothermal heat pump could add additional capacity to the solar/heat storage system.

11) Heat storage. With a larger system of heat storage, we could capture enough heat for several weeks or even months, and if large enough it would be sufficient for the entire winter. The rationale behind such a system is that solar heat is unavailable during the night and in our climate sometimes for several weeks during cloudy periods. If the collectors are oversized then the excess heat can be stored, providing a backup to obviate the use of a furnace during cloudy periods. The solar panels and the heat storage device are the main investments for such a project, but these costs replace the fuel cost over the lifetime of the system. Typically for a small to medium sized heat storage, the payback period is ~30-50 years, but because it is sustainable it is worth considering a longer payback period. There are several methods for constructing a sufficiently large seasonal heat store.

The advantage of storing heat in a large tank of liquid is that the heat can readily be transferred and circulated through the building. However, the amount of water required to store heat for several months is large. From our energy audit, the building needs 24 kW to heat during a temperature difference of 18 degrees C. If we insulate the building with 4-times its current thermal R-value, the building would only require 6 kW.

Five months of storage. To store enough heat at a 60 deg C rise (35 degC -> 95 degC) over 5 months we would require a very large tank:

$$6\text{e}3\ \text{W} * \frac{5\ \text{mo}}{60\ \text{K}} * \frac{\text{J}}{\text{W} * \text{s}} * \frac{4.186\ \text{cal}}{\text{J}} * \frac{\text{g} * \text{K}}{\text{cal}} * \frac{\text{cm3}}{\text{g}} * \frac{\text{m3}}{1\text{e}6\ \text{cm3}} * \frac{2.592\text{e}6\ \text{s}}{\text{mo}}$$

6 * 5 * 4.186 * 2.592 / 6 * 1e2 = 5.425e3 m3 = tank 3m * 42m * 42 m

In other words, if we had a tank 10' high, and 138' x 138', we could heat the water up to 95 deg C, exchange its heat into water circulating through the radiator system, and it would heat the insulated meetinghouse for 5 months. The tank would have to be well insulated and constructed from durable materials to contain the hot water. This storage tank would be impractical because of its size and cost, but there are several alternatives.

Day or weeks of storage. If instead we should use a smaller water tank, the amount of heat stored would be proportionately less, which would require another system for backup, but the initial capital cost would be lower. An advantage of a small water tank is that it can be heated up to a high temperature more quickly, allowing a solar panel system to heat the building overnight unaided, after a few hours of clear sunlight. For example, we could take advantage of sunny days by storing heat in a tank big enough enough for 3 days of storage. The tank would need to be 6' x 25' x 25', which would fit in the basement. A larger storage tank, good for 2 weeks of storage, would need to be 6' x 46' x 70', which although quite large would still be within the realm of possibility.

Stratification of hot water. The performance of such a system could be improved by stratifying the hot water storage, so that the newly-generated hot water is stored separately from the warm water previously generated. This allows the hot water to be used for immediate heating at higher efficiency. This type of stratification can be accomplished with several smaller tanks connected in series, with the bottom of the hotter tank connected to the top of next cooler tank, or by horizontal baffles within a tank. The hot water from the heat source (solar panel or geothermal heat pump) would then be circulated through the uppermost tank, and as the return water warmed up, it would be circulated through the cooler tank.

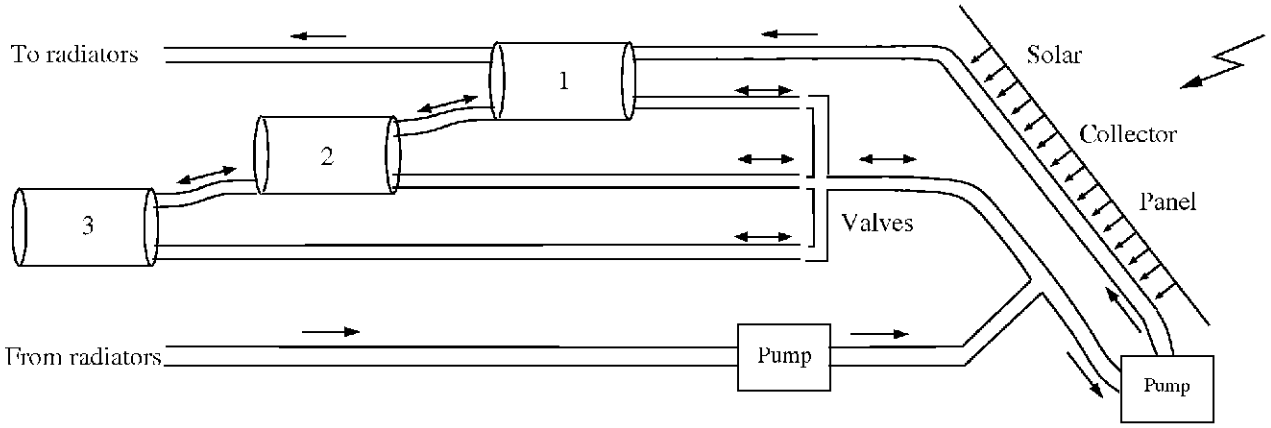

Figure 7. To store heat most efficiently, solar storage tanks are connected in series, with the bottom of the first tank connected to the top of the second, and so forth through several storage tanks. When hot water is circulated from the solar collector panel (right), the first tank is at first heated quickly by circulating its near outlet back to the collector. When the first tank is up to temperature, the second tank is connected into the loop. By filling smaller tanks with hot water from top to bottom, the water is kept hot. To retrieve the heat most efficiently, it is taken from the top of the hottest tank.

Water and rock storage. Because rock has greater heat capacity than water, a tank filled 90% with rocks can store ~2-fold more heat than the same tank filled with water. This would allow the 2-week storage tank to be reduced to 10' x 30' x 30'. A tank this size could be constructed of insulated concrete, in 2 sections, each 10' x 15' x 30'.

Seasonal heat store. With a more ambitious system of heat storage, we could capture enough heat for several months. The rationale behind this system is that heat is inexpensive to capture during the summer, allowing a modest investment in solar panels to capture enough heat for part or all of the winter. A seasonal heat store system captures heat from the summer sun in July - September, and then stores it for use during the winter months. This would require a large insulated heat storage device underground.

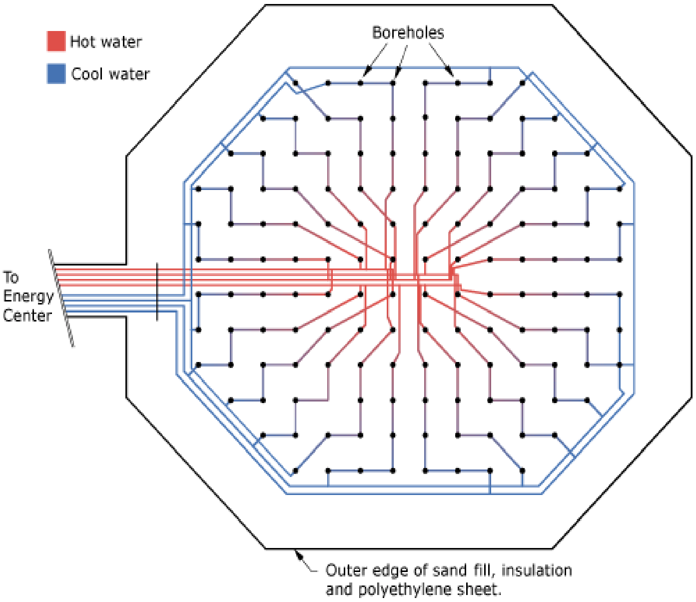

Figure 8. Seasonal heat store consisting of 144 boreholes, each 6" in diameter and 120' deep, spaced 7.5' apart. The innermost boreholes are charged with heat from solar panels during the summer and can store an enormous amount. During the winter the flow is reversed and the innermost boreholes generate hot water to heat the buildings, and the outer boreholes are cooler and receive the cool water return. The system is designed to store all the heat necessary for the winter. From www.dlsc.ca.

Earth storage. Because earth has a higher heat capacity than water, it is possible to efficiently store heat in a large volume of earth. Heat can be discharged or recharged from a volume of earth with water circulating through embedded coils of tubing. The main difference from a water heat storage system is that the embedded tubing must be longer because of the higher storage capacity and lower thermal conductivity of earth. Therefore the tubing used for earth storage will have higher thermal resistance and greater resistance to flow. This can be resolved by connecting several tube runs in parallel. An excavation to 20' will allow insulation to be laid over a wide area, then covered by earth, then tubing laid and then recovered with earth to grade.

Borehole storage. A field of several dozen boreholes of sufficient depth can store heat in the earth (see refs below: www.dlsc.ca). This is much cheaper than water storage, for several reasons. The boreholes cost less than a large tank, they can be drilled much deeper than practical for a water tank, thereby consuming less land area, and the heat capacity of earth is significantly (2x) greater than for water. With some resourcefulness we might arrange a borehole storage field on our campus that would suffice for heating our buildings over the winter. The borehole field is insulated on the top with foam panels underneath a covering of sand and topsoil so it can be landscaped to be a green area or playground. The sides and bottom of the borehole field are uninsulated but the surrounding earth becomes part of the heat store and gradually accumulates heat over a full season. The boreholes on the edge of the field are cooler, and these accept the cool water returned from the building's heating system.

The borehole field takes several months to heat up but when fully charged with heat can supply heat at a temperature sufficient for direct use by a hot water radiator system.

Typically a borehole heat storage system is combined with a system of temporary heat storage that holds recently captured heat in an insulated water tank. This tank is compatible with a heat pump and also with a hot water furnace. When more heat is accumulated in the temporary storage than is required by the building, it is directed into the borehole storage.

One problem with borehole storage can prevent good efficiency. If the boreholes are located in an aquifer with moving water, the heat may be lost over several months because the heated water moves away from the boreholes. Even fraction of an inch a day could reduce efficiency. To prevent this problem, a site without moving water must be selected. Our campus is on the side of a hill and is known to have springs nearby. It would seem difficult or impossible to ensure that the water near the boreholes would stay put.

Practical plan for 30 days of storage with backup. If we combine several of these methods, we could design a solar heat storage system combined with a geothermal backup to give reliable and cost-effective heating over the winter. To be an effective solar heat system, the storage capacity would need to be sufficiently large for several weeks. This would allow heating the building during a cloudy spell. The extra heat stored would reduce the fraction of time a backup heat source would be required. We could construct a system with stratified hot water tanks with enough capacity to directly heat the building for several days and nights. Then, we could add heat storage in a volume of earth sufficient for several weeks, to be recharged by solar heat during sunny days, and to be discharged when required over several weeks to a month. The earth heat storage, if kept in the range of 70-90 degrees could be accessed with a heat pump efficiently because a heat pump's efficiency is greatly enhanced when pumping over 10-20 deg F. If during a long cloudy period the earth heat storage was completely discharged, the heat pump could be switched over to geothermal wells which are more reliable but less efficient because the deep earth temperature is 55 deg F.

To minimize use of the heat pump in such a system, it would be important to carefully plan the solar collector capacity, and therefore to plan the improvements in the building's insulation carefully to minimize the amount of heat required. The fraction of excess heat collection capacity would determine how fast the stratified hot water tanks would be recharged and how many days of sunlight would be necessary to recover from a prolonged cloudy spell. The reliance on a heat pump, although it would seem unnecessary in a storage system hot enough to heat the building directly, would allow reliable heating from a storage system that is not always maintained at a high temperature. This would provide a cost benefit over a geothermal heat pump without storage.

12) Payback. All of the options described above are expensive and will require a large capital investment. However, they will all pay back reliably in several decades, depending on the cost of energy, and we should consider all of them to increase the sustainability of the Meetinghouse. The options to consider first are those with the most immediate payback.

However, we should consider all of the options together because the use of energy is a long-term certainty and the long-term options depend on which short-terms we complete and how we accomplish them.

13) Agenda. We should consider carefully how to proceed to maximize our cost savings and sustainability. There are several obvious steps:

a) Super-insulate the Meeting Office with external insulation and high-efficiency storm windows. Contract with an architect and engineer to specify in detail how the insulation is installed. Ensure that a vapor barrier is installed underneath the exterior insulation, and that adequate venting to release vapor on the outside of the existing wall is included. Check the progress and outcome of this installation, to see how well the installation proceeds. Once the super-insulation is in place, measure the heat load and calculate the necessary heat pump capacity. Our existing air-to-air heat pump in the office can provide both heating in the winter and cooling in the summer. This provides the immediate benefit that the main meetinghouse furnace does not need to be activated.

b) Super-insulate the Committee Room, Social Room, and Kitchen with external insulation, attic insulation, and replace the storm windows with double- or triple-pane windows. Apply 4" of foam insulation on the stone walls, and pay special attention to the joints around the doors and windows. This will provide an immediate benefit in terms of energy savings. Once the energy use is reduced by the insulation, measure the heat load and install a hot water radiant heating system in the floor, powered by several smaller condensing type furnaces. As our experience increases with external insulation and high-efficiency storm windows, we will then be in a position to work on the main Meeting room.

c) Install geothermal wells for a heat pump system to heat the Committee and Social Rooms and Kitchen. The wells can be drilled nearby the meetinghouse and could be combined with a heating system for the Meeting Cottage.

d) Super-insulate the main Meeting Room. This can be based on our experience with insulating the Office and Committee and Social Rooms. Apply foam insulation, Changes to the Meetinghouse's appearance should be minimized by a careful attention to application of the stucco to the exterior surface and the attention to detail around windows.

e) Ask the engineers to design the most sustainable heating system for a payback period of 50 years. This could include geothermal, solar, and seasonal heat stores. It might also be combined with an integrated system for heating all the buildings on campus. We might install seasonal heat store boreholes under the commons area or playground areas.

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